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PROBABLE MAXIMUM PRECIPITATION FOR CALIFORNIA

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ABSTRACT

This study provides estimates of general-storm probable maximum precipitation (PMP) for drainages in the state of California for durations of 1 to 72 hours, for areas of 10 to 10,000 mi^2, and during any month of the year. The report also provides estimates of local-storm PMP for durations of 15 minutes to 6 hours in drainages of 1 to 500 mi^2. Step-by-step procedures are given along with example calculations.

Comparisons are made to its predecessors, Hydrometeorological Report No. 36 (1961) and Hydrometeorological Report No. 49 (California area, 1977); to extreme precipitation values from major storms in California; to record-setting rainfalls at individual locations; and to 100-year rainfall frequency values from NOAA Atlas 2 (1973). The comparisons indicate that the PMP estimates of this report are consistent and reasonable.

A computerized storm analysis scheme was developed and implemented to examine 31 major storms. Updated maximum persisting dewpoints and sea surface temperatures were used in the storm analyses. Many of the calculations, comparisons, and analyses involving spatial relations were facilitated by using a geographical information system (GIS). The plates accompanying the report and all of the figures are digital products.

1. INTRODUCTION

1.1 Background

Generalized estimates of probable maximum precipitation (PMP) for Pacific Ocean drainages of California were first published by the National Weather Service (NWS) as Technical Paper No. 38 in 1960, and followed by Hydrometeorological Report No. 36 (1961), which was printed with revisions in October 1969. PMP estimates were provided for general storms from October through April. General-storm estimates of PMP for southeast California (mostly desert) were presented in Hydrometeorological Report No. 49 (1977). Hydrometeorological Report No. 49, which examined the Colorado River and Great Basin Drainages, also provided estimates of local-storm PMP for all of California. None of the reports provided general-storm PMP estimates for most of northeast California. In this report, publications in the Hydrometeorological Report series, such as Hydrometeorological Reports No. 36 and 49, will be abbreviated as HMR 36 and HMR 49.

HMR 36 used a mass-conservation model as a primary tool to develop estimates of general-storm PMP in topographic regions, but was unable to account for local convergence, convection, and synergistic effects caused by natural upper-level seeding of low-level clouds in orographic regions (Browning 1980, Hobbs 1989). This last effect is sometimes called the *seeder-feeder* effect. It is caused by convergence of moisture and upward vertical motion on the windward side of a mountain, with precipitation from the upper levels seeding and feeding (enhancing) the lower levels, resulting in increased precipitation on the ground. Presently, no numerical model of atmospheric processes can completely replicate orographic precipitation, especially quantitative amounts, in a reliable manner, especially for extreme general storms (Cotton and Anthes 1989, Katzfey 1995).

HMR 57 (1994), a recent PMP study for the Pacific Northwest, showed some major differences between general-storm PMP estimates at the California-Oregon border, and local-storm values, especially in the western half of California. In addition, some intense storms that occurred since the publication of HMR 36 had many precipitation amounts that approached, and in a few instances surpassed the PMP estimates given in HMR 36. As a result, it was decided that PMP estimates for California needed to be examined using new storm data and new techniques for an orographic region, which uses storms as the basis for establishing PMP.

Due to continued and strong interest in the operational products (maps, tables, diagrams, etc.) and techniques developed in this study, expressed to the Hydrometeorological Design Studies Center by some within the hydroelectric and hydrometeorological community, it was decided to present the calculation procedures in a separate report, HMR 58 (1998), prior to release here. Chapter 13 and Appendix 4 of HMR 59 constitute the preponderance of material in HMR 58. Chapters 2 through 9 of the present report provide the rationale for the computational procedures described in HMR 58.

1.2 Authorization

The authorization to develop new PMP estimates for California was given by the United States Army Corps of Engineers Office of Civil Works. Funding for this work was received from the United States Army Corps of Engineers and the Corps of Engineers Los Angeles District Office, South Pacific Division. Appropriations supporting the National Weather Service (NWS) effort were provided through a continuing Memorandum of Understanding between the NWS and the Corps of Engineers (COE). The Bureau of Reclamation (BOR), through its Flood Hydrology Group in Denver, provided insight, ideas, and reviewed the work throughout the study, giving many helpful suggestions and comparisons.

Many review meetings were held from 1992 to 1997 to share the progress being made in the development of California PMP estimates. Regular attendees, known as the Federal Interagency Team, were representatives of the COE (Office of the Chief Engineer, South Pacific Division, and the Los Angeles and Sacramento Districts of the South Pacific Division), BOR, Federal Energy Regulatory Commission, and the NWS. Many comments and suggestions made by this group improved the final estimates presented in this report.

1.3 PMP Definition and Philosophy

The PMP definition used for this report was given in HMR 55A (1988) as "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year." This is slightly different from the previous definition (American Meteorological Society 1959), which was used in HMR 36. The HMR 36 definition stressed that the estimate was for a particular drainage area. The current definition is more generalized, and emphasizes the control the atmosphere has over a broad geographic region. At the same time, the techniques from this report provide estimates of PMP for specific basins.

Intense storms are the building blocks of PMP estimations (Schreiner and Riedel 1978, Hansen et al. 1988, Vogel 1993, Hansen et al. 1994). Precipitation totals from the most intense storms of a region represent the lowest potential levels of PMP, and provide a first measure of an optimum set of atmospheric moisture and dynamics that can produce intense precipitation rates and amounts. A basic assumption is that the record of intense storms is sufficiently large that an efficient *storm mechanism* has been identified, but the observed storms have not attained the optimum moisture and energy levels necessary to produce a PMP event (Showalter and Solot 1942, Cudworth 1989).

The atmospheric conditions considered important to the formation of storms used in the estimation of PMP are: 1) abundant atmospheric moisture, 2) an efficient precipitation-producing mechanism, and 3) an intense storm system. Another assumption is that there is a sufficiently large catalog of such storms to describe the optimum storm mechanism for producing a PMP event. However, even though about 100 years of intense storm information is available, such storms have not been observed over all areas of a region. To overcome this lack of storms, three important tools are used in the estimation of PMP: moisture maximization, storm transposition, and envelopment.

Both moisture maximization and storm transposition consider the moisture content of the atmosphere and the efficiency of the storm mechanism that produces the precipitation. *Moisture maximization* is the process by which extreme observed precipitation is increased to a value consistent with the maximum potential moisture in the atmosphere for that storm location at that time of the year. A ratio is formed between the maximum moisture the atmosphere could hold at that time of the year and the actual moisture observed in the storm, and becomes a multiplier of the precipitation. This assumes that the storm would produce precipitation at the same efficiency.

Storm transposition is the relocation of the precipitation from an intense storm to another area that is climatically and geographically homogeneous with regard to extreme precipitation. Again, because of the inadequate sample of intense storms, it is necessary to assume that an extreme storm can be moved from its original location to a region in which climatology shows that similar storms, possibly of lesser intensity, could occur. This assumes that at least one storm in the sample has achieved maximum precipitation efficiency.

Envelopment is required because even some of the most intense storms have not reached maximum intensity over all areal sizes and durations. As a result, more than one storm is used over a region to define the temporal, areal, and seasonal distribution of PMP. During PMP development, where envelopment occurs, every effort is made to keep envelopment of values to a minimum. The method is primarily used to keep discontinuities to a minimum. In some instances there are areas where no major storms have been recorded. In such cases, it is necessary to infer PMP characteristics between regions, and this is done by smoothing gradients from one region to another.

The PMP storm for a region is considered the upper limit of precipitation. Moisture maximization, storm transposition, and envelopment are tools that provide estimates of the upper limits of precipitation for a region from intense storms. However, the remaining procedures used to develop a PMP design storm do not maximize the other factors involved in the estimation of these potential storms. Moisture is maximized, but other factors are allowed to act in a lesser manner, so that an unreasonable compounding of extremes does not occur. These procedures produce a PMP design storm. For orographic regions, only that portion of the precipitation that can be considered non-orographic is transposed. No attempt is made to transpose the orographic components of a storm.

1.4 California Terrain and Climate Influences

California provides several interesting challenges for estimating PMP. First, there are a complex series of mountains and valleys. Often the mountains act to enhance precipitation, but sometimes they shield areas from intense precipitation, and precipitation on the lee side quickly decreases. Both of these effects must be considered. Precipitation in the Central Valley behaves very differently than the rains in the surrounding orographic regions. Furthermore, the rainfall in the northern and southern parts of the Valley has quite different influences on it, depending upon the season. The most intense storms in the Pacific drainage region occur during winter. However, southern California is also affected by decaying tropical storms that form off the western coast of Mexico and move into the region. Over the desert areas of southeastern California the maximum PMP is caused by decaying tropical storms from July through September. Further challenges occur because the warm season produces severe local storms over all of California. These storms produce intense heavy rains over areas of 500 mi^2 or less and occur in 6 hours or less. Such estimates are especially important over small basins. Like the Pacific Northwest, California has varied sets of terrain, storm, and climatic relations that makes the estimation of PMP, or any other climatic factor a challenge.

1.5 Scope of Study

The entire state of California is considered in this study. HMR 36 only developed general storm PMP estimates for the Pacific drainages. As a result neither Northeast nor Southeast California were considered. General storm PMP estimates for the desert regions were defined in HMR 49. The only generalized PMP that was previously defined for Northeast California was compiled by Riedel (1985). Local-storm PMP for California was not defined in HMR 36, but was included in HMR 49. For this report estimates of PMP for both general and local storms are provided.

General storms are major synoptic events that have intense precipitation for durations from 6 to 72 hours or longer, and cover areas greater than 500 mi^2, often more than 10,000 mi^2. Local storms occur individually or are embedded in a larger storm system, and are characterized by intense precipitation in 6 hours or less and over 500 mi^2 or less. Most often these rains occur in thunderstorms. Observations indicate that both general and local storms can occur anytime of the year. However, general-storm precipitation maximizes during the winter months; maximum local-storm rainfall occurs most often during the warm months. In the Southeast desert, the dominant general storms are decaying tropical storms that occur from July through October. Over the Pacific drainages of California, local storms very seldom occur during the height of summer (July and August).

It was agreed by the Federal Interagency Study Team that the PMP general storm estimates would be limited to 72 hours or less and the areal coverage would be 10,000 mi^2 or less. Local-storm rainfall would be limited to areas of 500 mi^2 or less and durations of 6 hours or less. General-storm PMPIndex maps (Plates 1 and 2) give the all-season estimates. Methods to obtain seasonal estimates for general storms are provided in Chapter 13. Local-storm estimates of PMP are given in Chapter 9, Figure 9.23 (same as Figure 13.21), and the method to obtain estimates of the local-storm 1-hour PMP are given in Chapter 13.

1.6 Method of Study

General and local all-season PMP estimates and their seasonal variation were determined primarily by an intense study of extreme storm events that have occurred over California and nearby states with similar climatic regimes. In addition, climatic studies of various precipitation-related parameters were also performed. General-storm PMP estimates were developed using the *storm separation* technique. This technique was originally developed and used in the area between the 103rd Meridian and the crest of the Rocky Mountains in HMR 55A, and then again for the Pacific Northwest HMR 57. The storm separation technique provides a way of maximizing and transposing storms by separating the dynamically-forced precipitation from the orographically-forced precipitation. This allows only the dynamic part of the precipitation to be maximized and transposed to other regions.

Extreme storms of record are used for this analysis. The precipitation in these storms is divided into convergence (non-terrain influenced) and orographic (terrain-influenced) components. The convergence component of precipitation in a storm, that part of precipitation due to atmospheric forcing, is used to estimate the convergence PMP within the region where this storm occurred. This is the value that is maximized and transposed. The orographic component of the storm is not used to compute the total PMP in other parts of the region. Rather the total PMP is established by defining an orographic factor or ratio (T/C), which is derived from the 100-year, 24-hour maps of NOAA Atlas 2. The T is the Total storm precipitation at a point, while C represents the Convergence component, or that part of the precipitation that would be expected if there were no orographic component. If there is no orographic component acting on the precipitation at a point, then T/C is equal to one. The storm separation analysis procedure is summarized in Chapter 6, and fully described in HMR 55A and HMR 57.

Many of the calculations, comparisons, and analyses involving spatial characteristics of PMP were performed via computer. A geographic information system (GIS) called GRASS (Geographical Resources Analysis Support System), was used extensively throughout the study to create maps which could then be combined with other maps (GRASS Version 4.0, Users Reference Manual, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois, 1991). The process consisted of digitizing isolines which are considered vectors in a GIS. Vectors are the computer interpretation of an isoline. An interpolation between vectors forms a continuous field of values called a raster field in which each point (or raster) on the map has a value. Sometimes the individual rasters are called cells or raster cells. Each raster cell was a 15 second by 15 second region (about 0.08 mi^2) and had a interpolated value related to it. Raster fields or layers can be manipulated mathematically with other layers covering the same geographic region, usually by multiplying or dividing one layer by another. The final PMP Index map was produced from many such calculations and combinations of raster layers. It was found that the GIS was very useful in expediting preparation of the many maps that would have taken much more time to produce manually.

1.7 Peer Review

In the past, peer review of these reports was limited to personnel in the Hydrometeorological Branch and the Joint Study Team. Interest in PMP has grown over the years because of the National Dam Inspection Act of 1972, which required certain dams to meet safety standards imposed by PMP events. As a result, many more people are interested in PMP analysis, as evidenced by a number of conferences and studies: Australian National Committee on Large Dams 1988; Federal Emergency Management Agency 1990; National Research Council 1985; National Research Council 1988; National Research Council 1994; Office of Water Data Coordination 1986. This report was submitted to and reviewed by the following: Catalino Cecilio, Robert Collins, Dennis Marfice, Douglas Morris, John Riedel, Maurice Roos, Louis Schreiner, Ronald Spath, and Richard Stodt. The following individuals from the U.S. Army Corps of Engineers provided valuable insights and guidance during review of this report: Earl Eiker, Richard DiBuono, Frank Krhoun. We extend our sincere appreciation for the competent and constructive reviews given by all reviewers. It is hoped that this report has been strengthened by the inter-action with such a cross section of the hydroelectric and hydrometeorologic community.

1.8 Report Organization

Chapters 2 through 8 present discussions of procedures and data used to obtain general-storm PMP estimates for California. Chapter 9 provides background, storms, and procedures used to develop local-storm PMP. Chapter 10 gives comparisons of general-storm PMP for individual drainages between HMR 36 and the present study. Chapter 11 contains comparisons to other HMR 36 PMP estimates, the 100-year return-frequency precipitation event, other adjoining PMP studies, and observed extreme rainfall amounts in California. Chapter 12 provides conclusions and recommendations from this study, and Chapter 13 presents the computational procedures, with examples. As mentioned in Section 1.1, Chapter 13 and Appendix 4 are the essential contents of HMR 58.

References follow the computational procedures in Chapter 13. Appendix 1 provides depth-area-duration tables of storms used in this study. Appendix 2 gives a discussion of the storms and their precipitation mechanisms that caused the intense rainfalls. Appendix 3 contains a list of 137 local storms. Appendix 4 contains information and all tables necessary to compute the snowmelt associated with a PMP storm. Appendix 5 reproduces information about the storm separation method from earlier hydrometeorological reports.

1.9 Definitions

<u>All-season</u>. The largest or smallest value of a meteorological variable without regard to the time of the year it occurred. In this report, the largest PMP estimate determined without regard to the time of the year it may occur.

<u>Among-storm</u>. A storm characteristic determined when values of various parameters may be determined from different storms. For example, a 6-hour/24-hour ratio, where the 6-hour value is taken from a different storm than the 24-hour value.

Atmospheric Forces. The forces that result only from the pressure, temperature and moisture gradients and their relative changes with time over a particular location.

Barrier Elevation. The height assigned to a location which reflects the presence (or absence) of terrain features that have a significant effect on the broad-scale moisture flow and precipitation processes.

Basin Shape/Drainage Outline. The physical outline of the basin as determined from topographic charts or field survey.

Dewpoint. The temperature to which a given parcel of air must be cooled at constant pressure and constant water-vapor content in order for saturation to occur.

Envelopment. The process of selecting the largest value from any set of data. By so doing, consistency is maintained among charts depicting data for a variety of area sizes or durations.

Generalized. When used as an adjective to modify names such as PMP or estimates or charts, it is to be taken in the sense of *comprehensive*, i.e., pertaining to all things belonging to a group or category. Thus, a generalized PMP map for a specific area and duration defines PMP for all points in the region; no location is excluded.

General Storm. A storm event which usually produces precipitation over areas larger than 500 mi^2 and durations longer than 6 hours, and is associated with a major synoptic weather feature.

Implicit Transposition. The regional, areal or durational smoothing used to eliminate the discontinuity created (during transposition of non-orographic components of precipitation) by limitations of storm history, quantity and quality of observations, and transposition boundaries.

Individualized. As applied to drainage estimates, indicates studies for specific drainages that include considerations for possible local influences. In the sense of applications to specific basins, it is commonly implied that information obtained from a generalized study will be processed and result in specific drainage-averaged values.

Local Storm. A storm event restricted in time and space. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than 500 mi^2. Frequently local storms will last only 1 to 2 hours and precipitation will occur over only 100 or 200 mi^2. Precipitation in local storms is considered isolated from general-storm rainfall.

Probable Maximum Precipitation (PMP). Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographic location at a certain time of the year.

Spatial Distribution. The geographic distribution of PMP for a storm area based on a storm with an idealized pattern.

Storm-centered. A characteristic of a storm that is always determined in relation to the maximum observed value in the storm as compared to the same factor for some other duration and/or area of the storm. For example, a storm-centered depth-area ratio relates the average depth over some specific isohyetal area of the storm to the amount at the storm center.

Temporal Distribution. The order in which incremental PMP amounts are arranged within the PMP storm.

Within-storm. A storm characteristic determined when values of various parameters are required to be from the same storm. For example, a 6-hour/24-hour ratio where the values for each duration are always selected as the maximum values for the particular duration in the same storm (see also Among-storm).

2. SIGNIFICANT GENERAL STORMS

2.1 Major General Storms of Record

A review of storms was performed to determine the largest precipitation events on record. Various data sources were examined to create a master list of storms in the period from about 1900 to 1990. Initially, the United States Corps of Engineers (USCOE) Storm Rainfall Catalog (USCOE 1945-) provided a foundation for much depth-area-duration (DAD) data information. Most of the older storms (1901-1945) came from this Storm Catalog, while Bureau of Reclamation and National Weather Service files were used to supplement the list. In an effort to define other important storms, a search was made of digital rainfall data from California, and were compared to the 100-year, 24-hour precipitation frequency of NOAA Atlas 2 (1973). Individual amounts from stations were put in chronological order to define other potential storms. In addition, extreme storms identified by Goodridge (1992) were examined to uncover other potential storms. Finally, those storms used in HMR 36 (1961), HMR 49 (1977), and HMR 57 (1994) were reviewed to assure continuity between studies as far as the storm sample was concerned.

These storms were primarily general storms; they had durations of 12 hours or more, and precipitation was widespread as a result of a major synoptic-scale disturbance, such as a low pressure system, strong frontal activity or remnant tropical moisture from a decaying tropical system. Other short-duration (6 hours or less), small-area (less than 500 mi^2) storms were considered for local-storm analysis, and are discussed in Chapter 9. The general storms are listed in Table 2.1, and geographic distribution of all but three are shown in Figure 2.1. Five of these storms: December 1921 (40), December 1937 (88), November 1961 (149), December 1980 (175), and June 1958 (1013) occurred outside of California, but within a few degrees north. Of these five storms, three (40, 88, and 175) are north of the region shown on Figure 2.1. The latitudes and longitudes indicated in Table 2.1, are for the maximum point rainfall for the storm.

A number of storms from Figure 2.1 are centered just north and east of Los Angeles in the San Gabriel - San Bernardino mountains, and another storm group is located in the

Table 2.1. *California general and seasonal storms.*						
Storm Number	Date	Latitude	Longitude	Barrier Elevation (ft)	24-hr/10-mi^2 Precipitation (in)	Area (mi^2)/ Duration (hr)
40	12/9 - 12/1921	48°01'	-121°32'	3200	8.58	27253/72
88	12/26 - 30/1937	44°55'	-123°38'	1500	10.76	13869/96
126	10/26 - 29/1950	41°52'	-123°58'	2000	15.84	80511/72
149	11/21 - 24/1961	42°10'	-123°56'	2700	10.90	20850/48
156	12/19 - 24/1964	41°52'	-123°40'	2500	16.23	1932/72
165	1/11 - 18/1974	41°08'	-122°16'	1900	10.63	2272/72
175	12/24 - 26/1980	44°55'	-123°44'	1400	9.22	24865/48
508	1/15 - 19/1906	39°54'	-121°34'	2600	14.77	10000/84
523	5/8 - 10/1915	40°42'	-122°26'	1800	10.51	20000/72
525	1/1 - 4/1916	39°48'	-121°36'	2000	10.12	30000/72
544	12/9 - 12/1937	40°11'	-121°26'	5500	15.29	20000/72
572	12/21 - 24/1955	37°59'	-119°20'	10500	13.42	30000/72
575	10/11 - 13/1962	40°02'	-121°29'	5500	19.71	10000/96
630	1/3 - 5/1982	37°05'	-122°01'	950	20.65	20000/60
1000	2/1 - 6/1905	34°30'	-119°10'	3000	9.34	20000/96
1002	2/27 - 3/3/1938	34°14'	-117°32'	4400	20.25	20000/96
1003	1/20 - 24/1943	34°12'	-118°03'	2100	22.90	30000/96
1004	11/17 - 21/1950	39°08'	-120°20'	6900	11.90	20000/102
1005	1/25 - 27/1956	34°13'	-117°31'	3900	11.45	10000/48
1006	9/17 - 20/1959	40°43'	-122°16'	1000	17.83	30000/48
1007	12/4 - 6/1966	36°17'	-118°36'	8000	21.69	30000/54
1008	1/23 - 26/1969	34°13'	-117°35'	5500	19.07	20000/80
1010	2/14 - 19/1986	39°54'	-121°12'	5200	18.12	30000/120
1011	9/25 - 26/1939	34°16'	-118°04'	2500	10.08	5000/42
1012	5/18 - 19/1957	39°57'	-121°27'	5200	7.23	20000/60
1013	6/1 - 2/1958	42°15'	-123°25'	3500	4.33	5000/48
1014	7/8 - 10/1974	38°50'	-120°41'	2100	6.85	10000/48
1015	8/13 - 16/1976	40°43'	-122°16'	1200	5.11	10000/48
1016	9/9 - 11/1976	34°20'	-117°03'	6000	15.10	20000/48
1017	8/15 - 17/1977	34°50'	-115°41'	3600	5.70	20000/60
1018	7/27 - 29/1984	34°58'	-115°31'	3900	5.79	20000/36

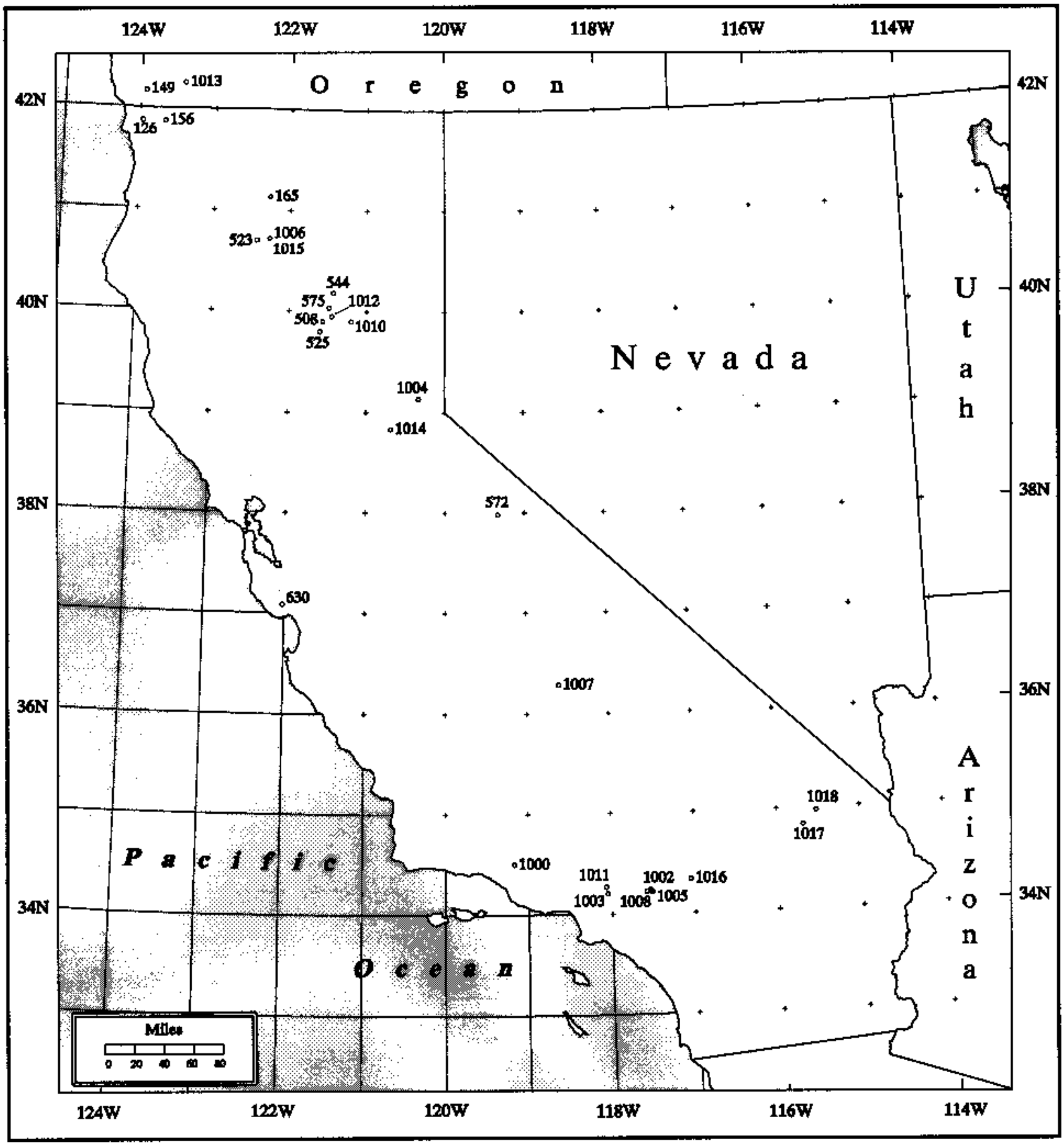

Figure 2.1. *Location of general storms of record from Table 2.1.*

northern Sierra Nevada mountains. In both locations terrain features served to focus and enhance precipitation in the passing storms. It is also true that, at least around Los Angeles, the raingage density is relatively high compared to the rest of the state. At the same time, there are immense areas where few storms are recorded due to a lack of systematic raingage records, most notably in the deserts of eastern California. Furthermore, many of the heavy rainfalls in the Central Valley are associated with storms centered in orographic regions.

2.2 Storm Data Analysis

An important part of the procedure to develop probable maximum precipitation (PMP) estimates is the analysis of the major storms in Table 2.1. Analysis includes: collecting precipitation data from various sources; applying quality control that identifies incorrect data; handling missing data; and compiling the data into a format for automated processing. The inclusion of a synoptic weather analysis for each storm is important to understand the timing and precipitation pattern for each storm. The synoptic analysis for each storm examines the surface and upper-air features, precipitation, and dewpoints and/or temperatures pertinent to the storm. Appendix 2 provides excerpts from the synoptic analyses for the most significant storms. Some of the other storms are discussed in HMR 36 and HMR 57.

The objective of the storm analysis was to obtain DAD information upon which to base PMP estimates, as well as generalized relations for other areas with similar climatic and topographic characteristics. The DAD information was used in the storm-separation process in Chapter 5, Section 5.4, and for the derivation of enveloped regionalized DAD relations in Chapter 8, Section 8.2. The numbers associated with the storms were assigned in no particular order. They are reference numbers that have been given to storms for filing and tracking purposes only. Storms with numbers less than 1000 were storms used in the derivation of PMP for the Pacific Northwest (HMR 57). Numbers greater than 1000 are an internal Hydro-meteorological Design Studies Center ordering system. All storms from Table 2.1 were analyzed to obtain DAD relations. In some cases, previously published pertinent data sheets, from the Storm Rainfall Catalog (USCOE 1945-), were re-analyzed. The procedure used to determine DAD for each of the storms is described in Chapter 5.

2.3 Characteristics of Wintertime and Summertime Extreme Storms

The analysis of synoptic weather relations for a PMP study is similar to the analysis used in the preparation of a weather forecast. *Synoptic knowledge* is applied to transpose storms and to regionalize DAD relations. The information required to calculate PMP for a region, does not depend directly on special insights about synoptic (or any other) scale atmospheric patterns, but is used to define the extreme storm types of a region and the generalized relations for similar regions.

The characteristics of various synoptic patterns associated with major precipitation-producing general storms in California are well-recognized and understood, and were described for all but southeast California in HMR 37 (1962). In 1981 the meteorology of important rainstorms was published in HMR 50 (1981) for the southwestern United States, and included storms from southeast of California. HMR 50 provides a thorough discussion of the observed and hypothesized sets of atmospheric patterns associated with extreme precipitation. Since publication of these reports, knowledge of the associations between weather and the structure of cyclonic storms and fronts has been much improved, e.g., Browning et al. 1973, Hobbs 1978, Shapiro and Keyser 1990, Martin et al. 1995. This increased understanding has provided added insight into the atmospheric structure for use in transposition and regionalization of storms.

A distinction is made in HMR 37 between summertime tropical and convective-like PMP storms, and wintertime orographic and convergence combined with convection PMP storm. This distinction remains relevant today. The summertime storms establish the annual or all-season levels of PMP for southeastern California; the wintertime storms set the upper limits for precipitation for the remainder of California. The conclusions related to the optimum wintertime atmospheric features expressed succinctly in HMR 37, have withstood the test of time. There is a basis to conclude:

> "that in the optimum storm, the band of high moisture transport has a degree of both persistence and stability of position which concentrates storm orographic precipitation totals. To this is added the conclusion that convergence precipitation characteristic of this storm may be centered within this band and that the most intense convergence precipitation may occur simultaneously with that of orographic precipitation."

Information from major storms occurring since 1962, remote-sensing data defining the storm environment, and storm simulation via numerical modeling have not changed or undermined these conclusions. The wintertime optimum conditions can be found everywhere except southeast California in varying degrees of strength and complexity. This is the basis for having only marginal differences in the DAD relations for all regions of the state except for the Southeast and to a lesser extent the Central Valley. These matters are discussed again in Chapters 6 and 7.

The atmospheric characteristics for all-season PMP storms in southeastern California were summarized in HMR 50. These characteristics include: 1) greater than customary amounts of moisture available for precipitation preceding the PMP storm, 2) maximum or near maximum values of sea surface temperatures off the west coast of Baja California, 3) an optimal track (both direction and speed) for tropical cyclones approaching southeastern California, and 4) an interaction with a *digging and deepening* cold trough or low pressure system aloft after the tropical cyclone arrives. However, not all of these features have been observed and recorded in southeastern California, but have been observed in Arizona. In the optimum PMP case these conditions could be assembled anywhere in southeastern California.

3. TERRAIN

3.1 Introduction

The climate and terrain of California are highly varied. The orographic complexity is largely responsible for the broad range of precipitation across the state. For example, Mount Whitney at 14,494 feet above sea level (ASL) in the Sierra Nevada is the highest mountain in the contiguous 48 states, and Badwater basin at 282 feet below sea level in Death Valley National Park is the lowest elevation in the United States. Several major mountain chains and many smaller ridges cover much of the region. Three notable mountain chains, the Sierra Nevada, the Coastal Range, and the San Gabriel-San Bernardino mountains have an especially important impact on precipitation. The Sierra Nevada chain has some of the highest mountains in California, with elevations surpassing 10,000 feet ASL, and runs north-south along the Nevada border. The Coastal Range, a much lower conglomeration of mountains ranging from 3000 to 6000 feet ASL, stretches the length of California along the Pacific Ocean with only minor breaks. Finally, the San Gabriel-San Bernardino mountains lie just north and east of the Los Angeles metropolitan area, with elevations above 10,000 feet ASL.

Surrounded by the various mountain ranges, the Central Valley extends from the Sacramento River basin in the north to the Imperial Valley in the south. Other notable low-level areas are found near Los Angeles and San Diego, nestled into areas bounded by mountains or the Pacific Ocean. Southeast California lies east of the major mountain areas, but contains a number of minor ridges and valleys. Another area of interest is the Salton Sea, surrounded by low-lying mountain ridges (3000 to 4000 feet) with some peaks to the west above 6000 feet ASL. Overall the mountains, valleys, and the Pacific Ocean make the climate of California unique and varied. Figure 3.1 shows the principal mountain ranges and major low-elevation areas in California.

All three mountain ranges block in substantial ways the dominant westerly or southwesterly moisture inflow. This leads to greatly enhanced precipitation along the windward side of these ranges and rainshadow effects downwind. Some of these

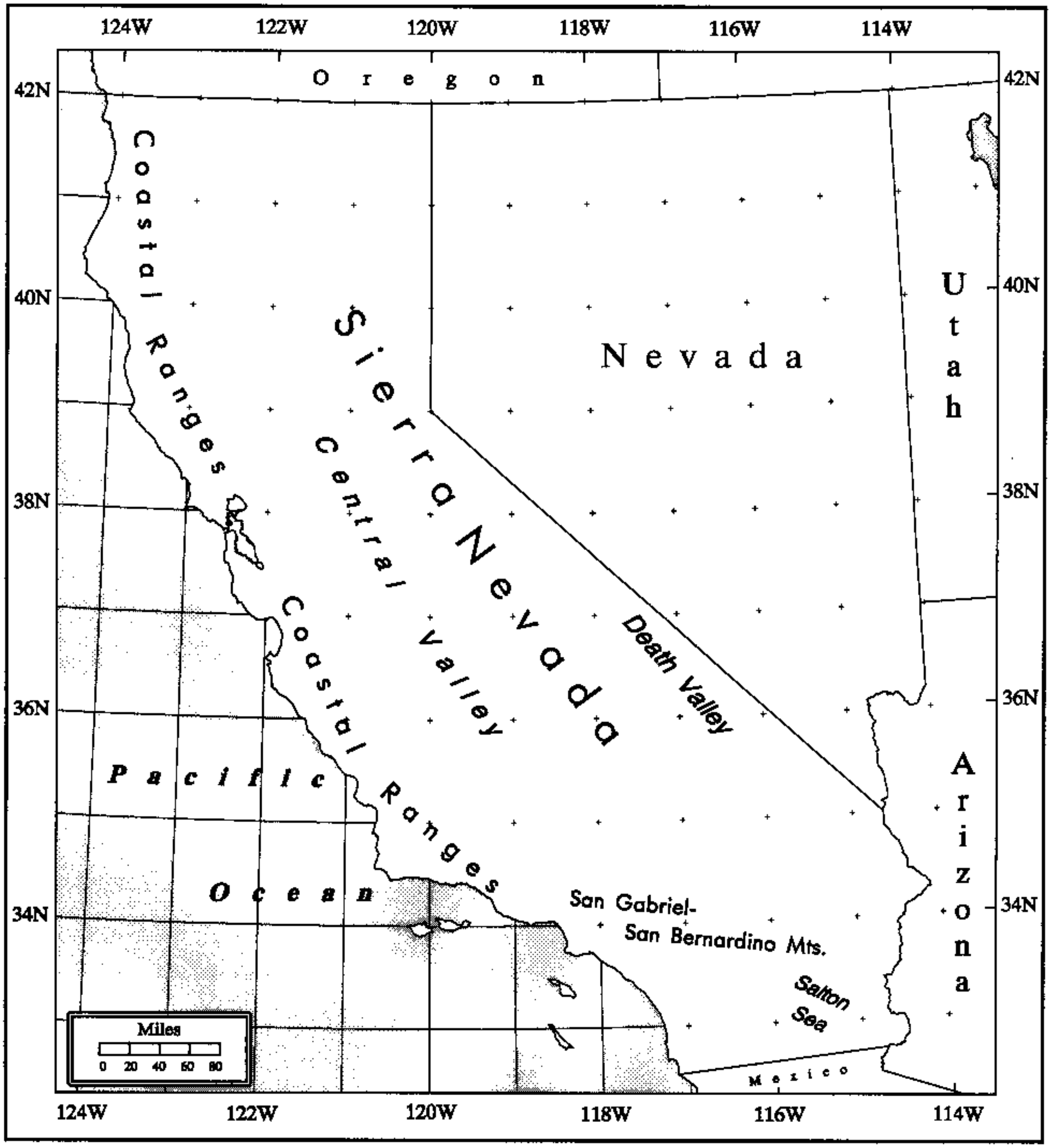

Figure 3.1. *Locations of principal mountain ranges and low-elevation valleys in California.*

characteristics are shown in the mean annual precipitation map (National Climatic Data Center 1992) in Figure 3.2. Average annual totals exceeding 70 inches are observed in the Sierra Nevada and along the Coastal Range in northern California. Average annual precipitation values exceeding 40 inches are found in the San Gabriel-San Bernardino mountains to the south. Note the relative lack of rainfall in the lee of orographic terrain. A large portion of California in the Central Valley and southeast California has yearly averages of less than 10 inches of rainfall. While Figure 3.2 includes the latest data updates, it is a computerized map that does not take into account the complex terrain of the region, but provides a generalized picture of mean annual precipitation.

3.2 Regional Analysis

Due to the widely differing terrain and orographic influences on precipitation California was divided into several regions shown in Figure 3.3. The regions were based upon terrain, similar climate zones, similar storm types, and precipitation characteristics. The regions also reflect variations in depth-area-duration (DAD) relations in California.

In order to represent meteorologically homogeneous regions several specific factors were considered. First and foremost, the individual storm DAD relations were analyzed and compared to one another to see how DAD relations vary by region. Second, obvious topographic differences provided guidance on how and where the boundary lines between regions were drawn. Third, the pattern of the 100-year, 24-hour rainfall frequency map from NOAA Atlas 2 (1973) shows the spatial variations in precipitation, thus providing a climatology.

The analysis resulted in seven distinct regions: Northwest (region 1), Northeast (region 2), Midcoastal (region 3), Central Valley (region 4), Sierra (region 5), Southwest (region 6) and Southeast (region 7). The Northwest region encompasses the relatively wet, rolling mountainous terrain of coastal northern California. The Northeast region represents the drier downwind zone of northern California, just north of the Sierra region. The Midcoastal region represents the low coastal mountains running along the California coast between the Central Valley and the Pacific Ocean. Sandwiched between the Midcoastal and the Sierra regions is the Central Valley region, constituting the flat, wide north-south plain of California. The final two regions include the Southwest, which is the mountainous area

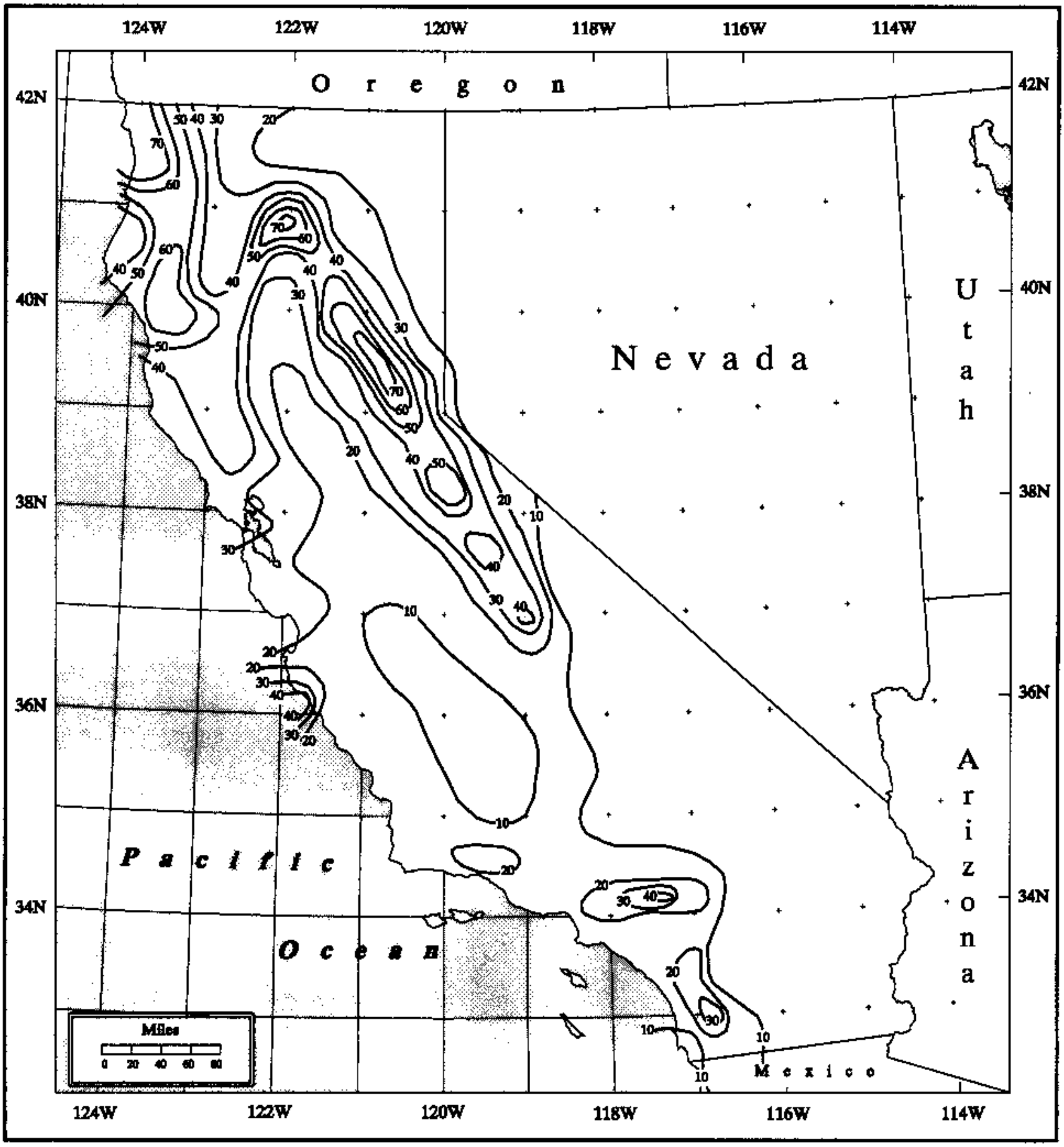

Figure 3.2. *Mean annual precipitation (inches) based on 1961-1990 normals (National Climatic Data Center 1992).*

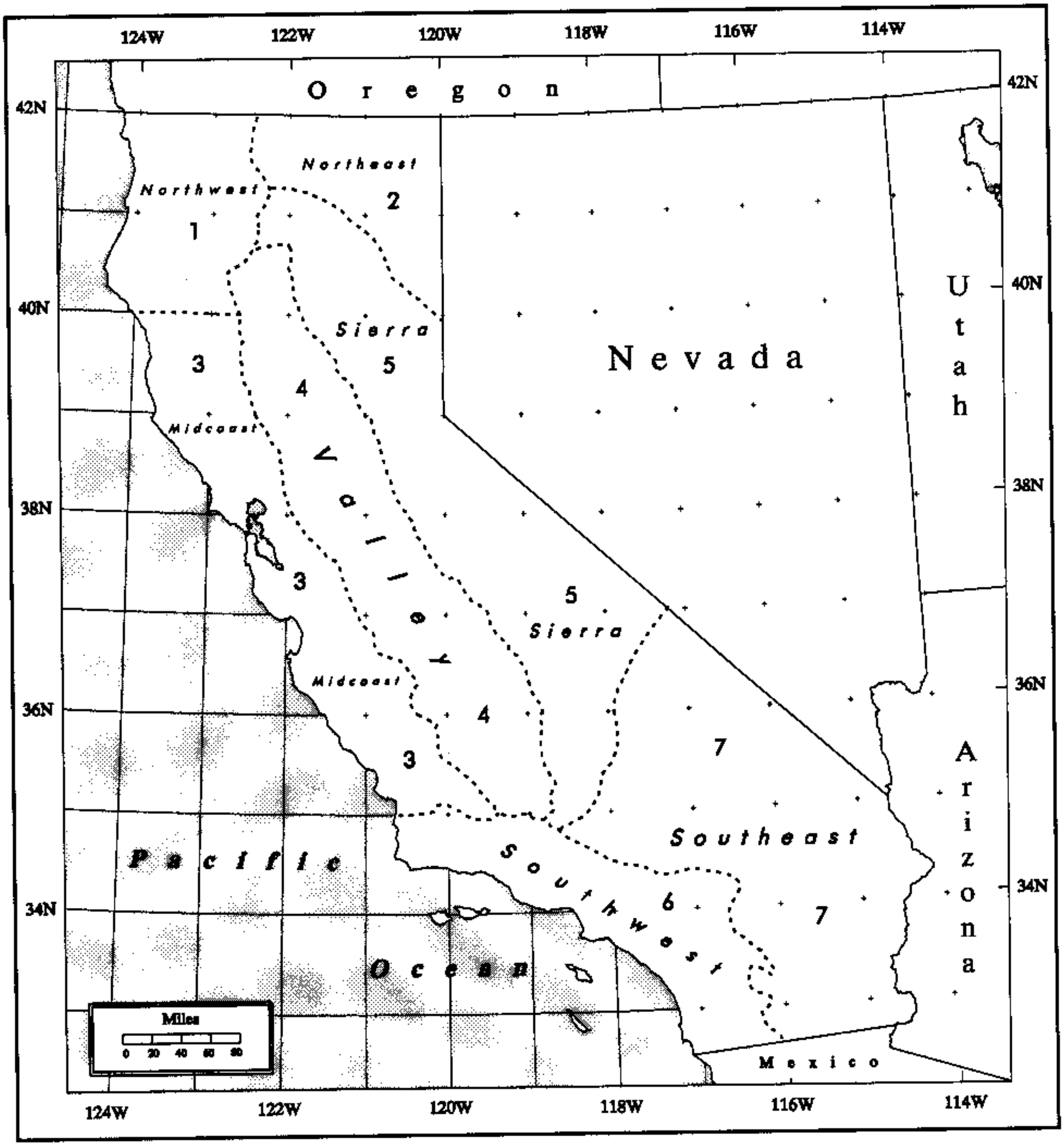

Figure 3.3. *Regional boundaries for development of depth-area-duration relations. Same as Figure 13.11.*

between the Pacific ocean and the deserts to the east, and the Southeast which encompasses the deserts of California. A complete discussion on the DAD relationships, and their derivation is found in Chapter 8, Section 8.2.

3.3 Barrier-Elevation

In this study, as in other studies, probable maximum precipitation (PMP) adjustments in the vertical must be made to precipitation and moisture values (dewpoints) to: 1) calculate orographic influence (K-factors), 2) define moisture maximization, and 3) adjust storm rainfall depths as the result of transposition. This adjustment is required because terrain interacts with the broad-scale winds and accompanying moisture flow when they encounter or are forced to bypass terrain features that act as barriers. The technique used to make barrier elevation maps has been discussed extensively in previously issued reports, (e.g., HMR 36 (1961), HMR 43 (1966), HMR 49 (1977) and HMR 55A (1988)). No changes from previous studies were made to derive barrier elevations.

The inflow wind directions used to construct the barrier elevation map ranged from south-southeast to west-southwest for PMP storms in the Central Valley, Sierra, and Midcoastal regions of the state and, from east through south for PMP storms in the Southeast region. The final barrier elevation map was hand-drawn at the 1:1,000,000 map scale, with topographic features less than 10 miles in width disregarded. The barrier elevation map is shown in Figure 3.4.

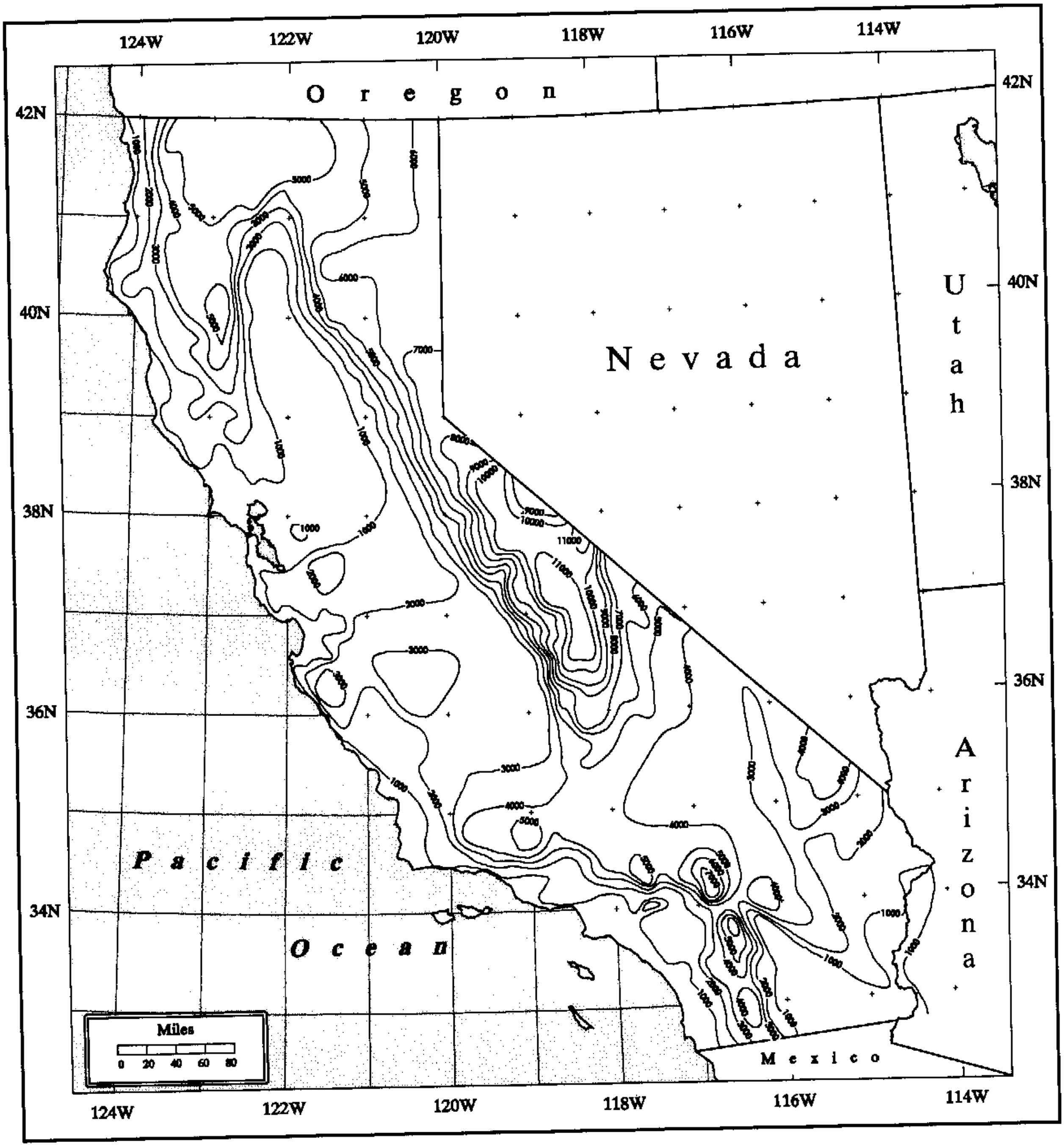

Figure 3.4. *Barrier elevations (whole feet MSL) for California.*

4. MOISTURE

4.1 Introduction

There are a number of ways to provide atmospheric moisture information for input into the calculation of probable maximum precipitation (PMP). The longest available record of moisture measurements are from surface observations. Early in the 20th century observations were only taken 2 or 3 times a day. In an effort to obtain the maximum possible record of extreme atmospheric moisture, these early measurements are used with more modern observations to provide a measure of extreme atmospheric moisture. A 12-hour duration was chosen to represent the general broad-scale flow into a storm with precipitation covering an area greater than several thousand square miles. Because of the limited observations taken each day in the early part of the century, a persisting dewpoint value was used to define maximum moisture. A maximum persisting dewpoint is the highest dewpoint equaled or exceeded throughout a given duration. It can be considered to be the highest, as indicated by the record, that can persist for various durations. Generally, the persisting value provides a lower value than a 12-hour average dewpoint. Surface values are observed at a number of different elevations. In order to compare values from different locations, the 12-hour persisting dewpoint is normalized or adjusted to the 1000-mb pressure level, or essentially sea level. This allows these values to be compared across the United States, in spite of large differences in the elevation of observations.

Charts of 12-hour maximum persisting dewpoint temperatures have been used in many HMRs including those for the western United States: HMR 36 (1961), HMR 43 (1966), HMR 49 (1977), HMR 55A (1988), and HMR 57 (1994). This extreme atmospheric moisture information is used to maximize observed storm precipitation, and to adjust storm precipitation for horizontal and vertical changes in storm location (transposition). Several studies (e.g., Reitan 1963; Bolsenga 1995) have shown that surface dewpoint temperature is an acceptable measure of water vapor aloft in the saturated atmosphere during storm periods. In addition, Kuo et al. 1996 indicates that the inclusion of surface moisture measurements in a variational data assimilation system can be "quite effective in...improving the quality of moisture analysis in the lower troposphere."

4.2 Dewpoint Analysis

In this study, we used monthly analyses of 12-hour maximum persisting 1000-mb dewpoints developed for the United States west of the Continental Divide for HMR 57. These analyses used synoptic time observations of dewpoint temperatures for 36 locations (Peck et al. 1977) as well as hourly dewpoint observations for 23 California locations obtained on tape from the National Climatic Data Center (NCDC) for the years 1948 to 1983. These data were examined for possible exceedances to the 1905-1959 set of data used in HMR 36. When such exceedances occurred, they were verified against values in the Local Climatological Data (NCDC 1948-). They were also checked with synoptic weather information to ensure that the new records occurred with conditions favorable for precipitation. When new dewpoint records occurred during precipitation sequences, the dewpoints were accepted, provided that upwind trajectories from the site showed increasing dewpoints over time. Once the new records were determined, new annual curves were drawn for these stations. Values from these curves were plotted on monthly maps and new analyses were drawn. Maps of month-to-month changes of persisting dewpoint values were made and individual monthly maps redrawn to obtain a smooth monthly transition of 12-hour persisting dewpoints across California. Monthly differences from the earlier reports were usually less than 2°F and none exceeded 3°F.

The dewpoint analyses shown in Figures 4.1 to 4.12 reflect seasonal-scale atmospheric changes or adjustments. The contours in these figures depict mid-monthly values. The contour configuration for November through April in Figures 4.11, 4.12, 4.1 to 4.4 (albeit weakly in April) reflects the persistent presence of (relatively dry) continental polar and mixed maritime and continental polar air masses in eastern California. The warmer land area in the central and western regions sustain a *wedge* of higher dewpoints during the *wintertime* months. The cold, off-shore ocean currents affect the recurvature of the contours along the coast line. May is seen as a transition month between these characteristic *wintertime* and *summertime* regimes (Figure 4.5.) Then the contour pattern for June through September in Figures 4.6 to 4.9 and weakly in October (Figure 4.10) is forced by circulation patterns which bring in high-moisture content air originating over the regions with high sea-surface temperatures (SST) in the Gulfs of California and Mexico.

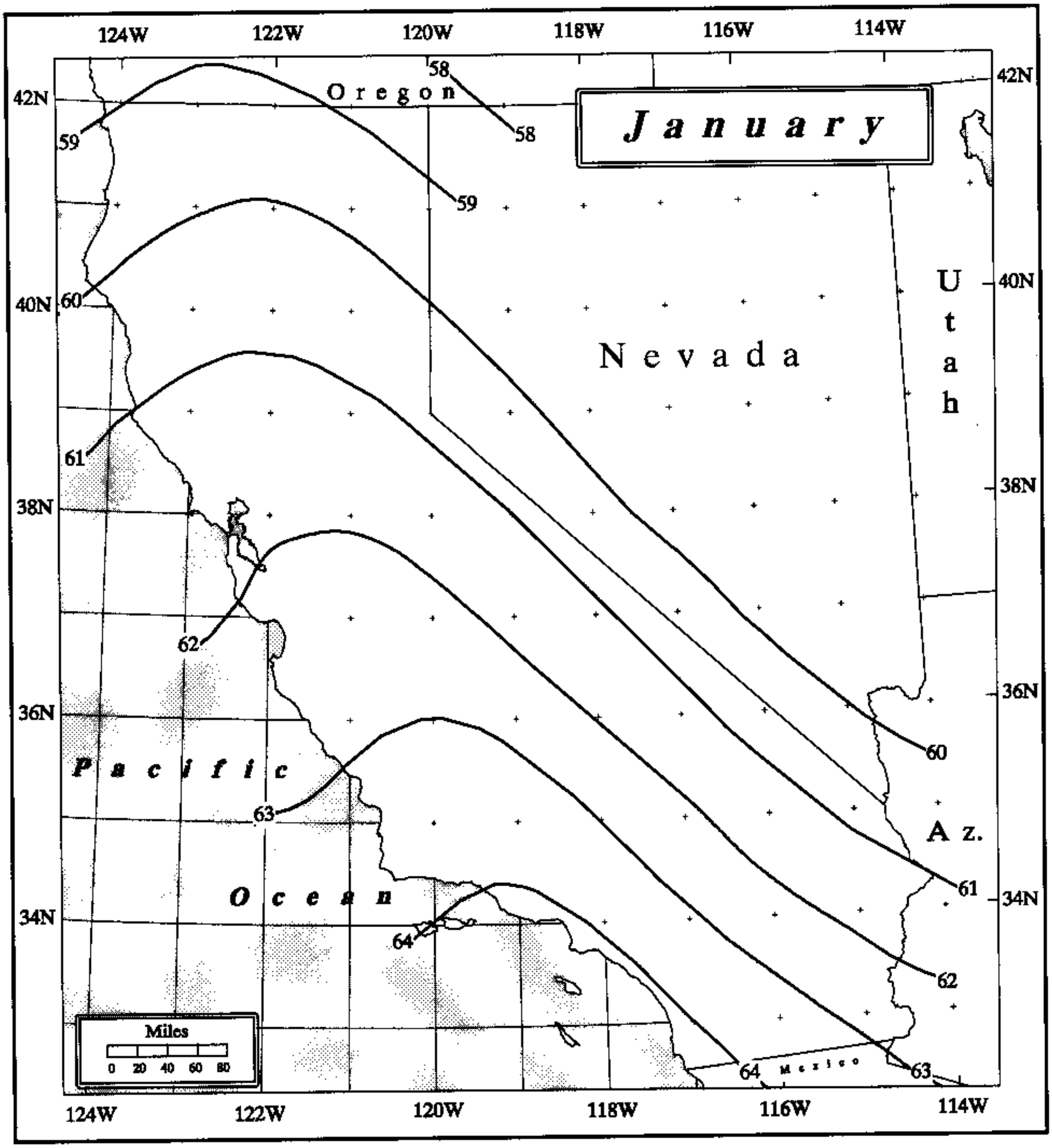

Figure 4.1. *Twelve-hour maximum persisting 1000-mb dewpoints for January (°F).*

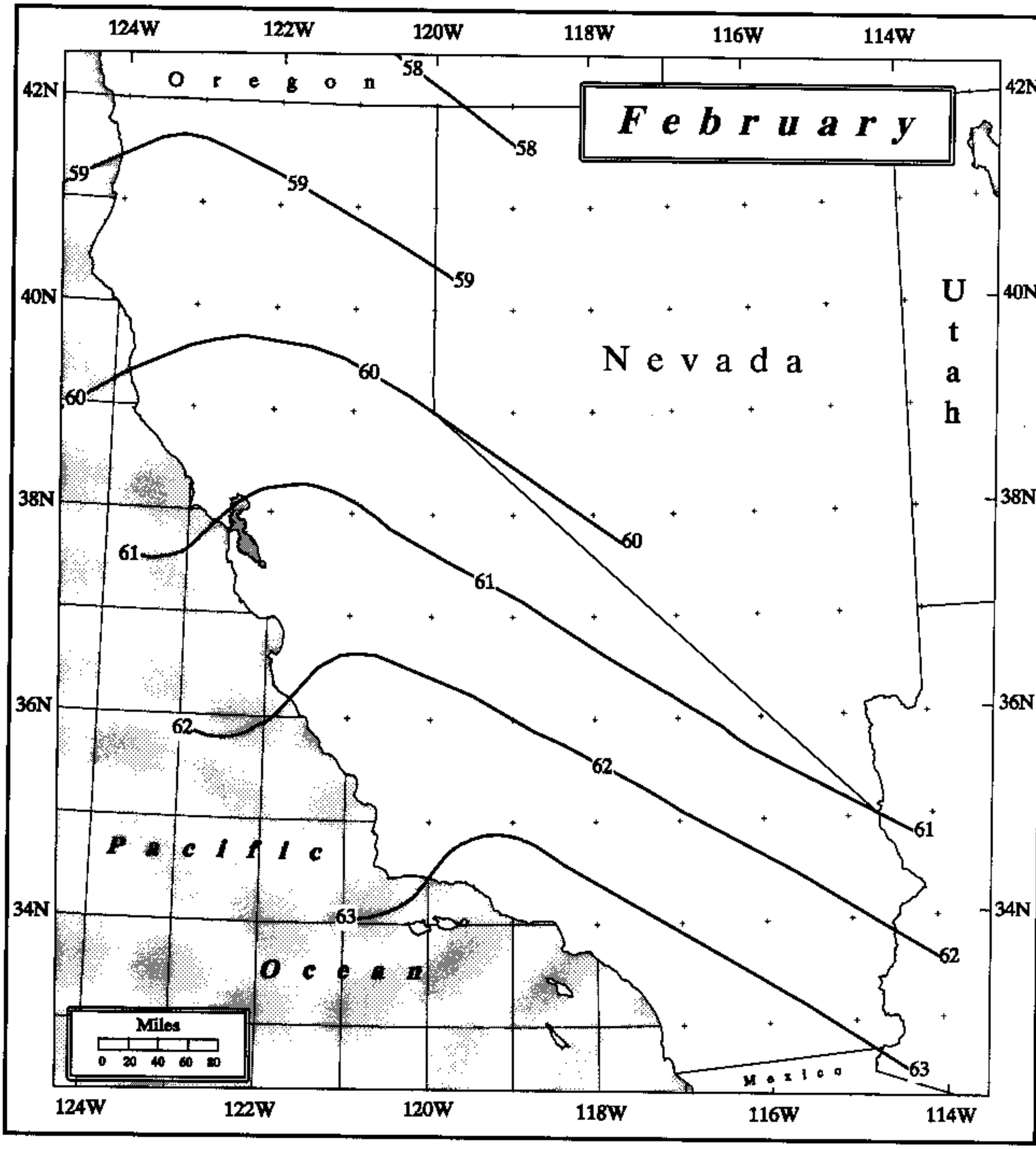

Figure 4.2. *Twelve-hour maximum persisting 1000-mb dewpoints for February (°F).*

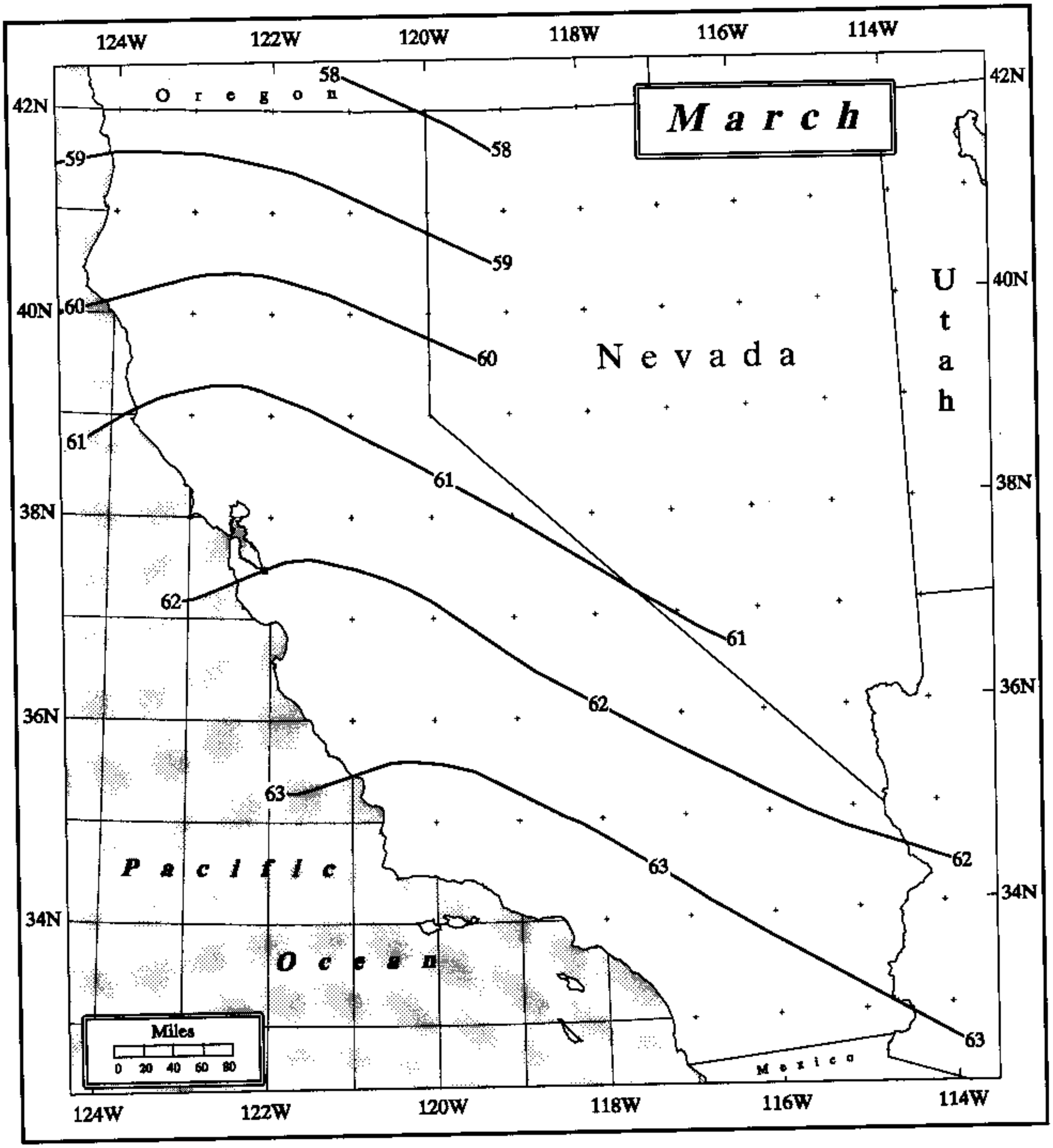

Figure 4.3. *Twelve-hour maximum persisting 1000-mb dewpoints for March (°F).*

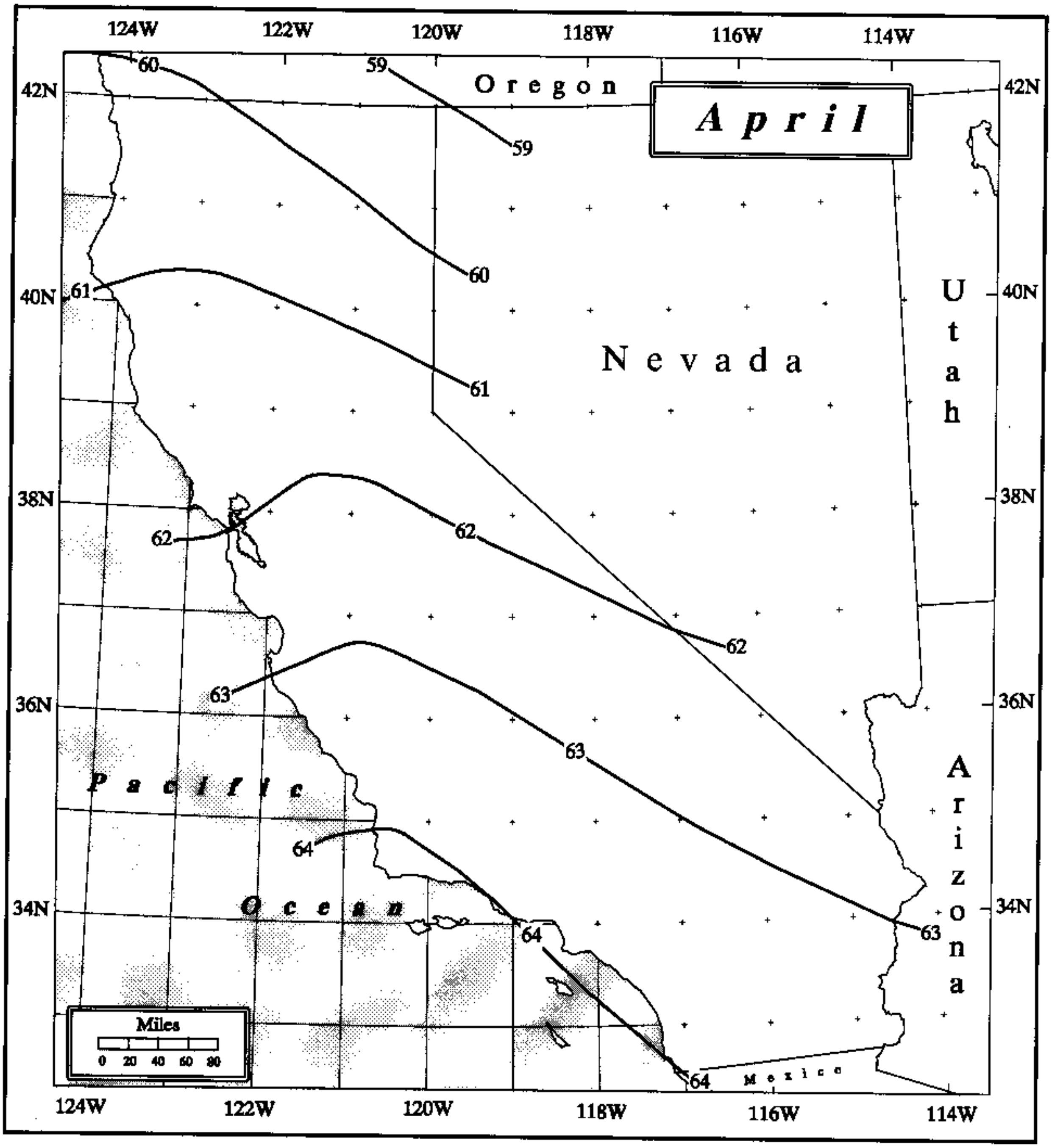

Figure 4.4. *Twelve-hour maximum persisting 1000-mb dewpoints for April (°F).*

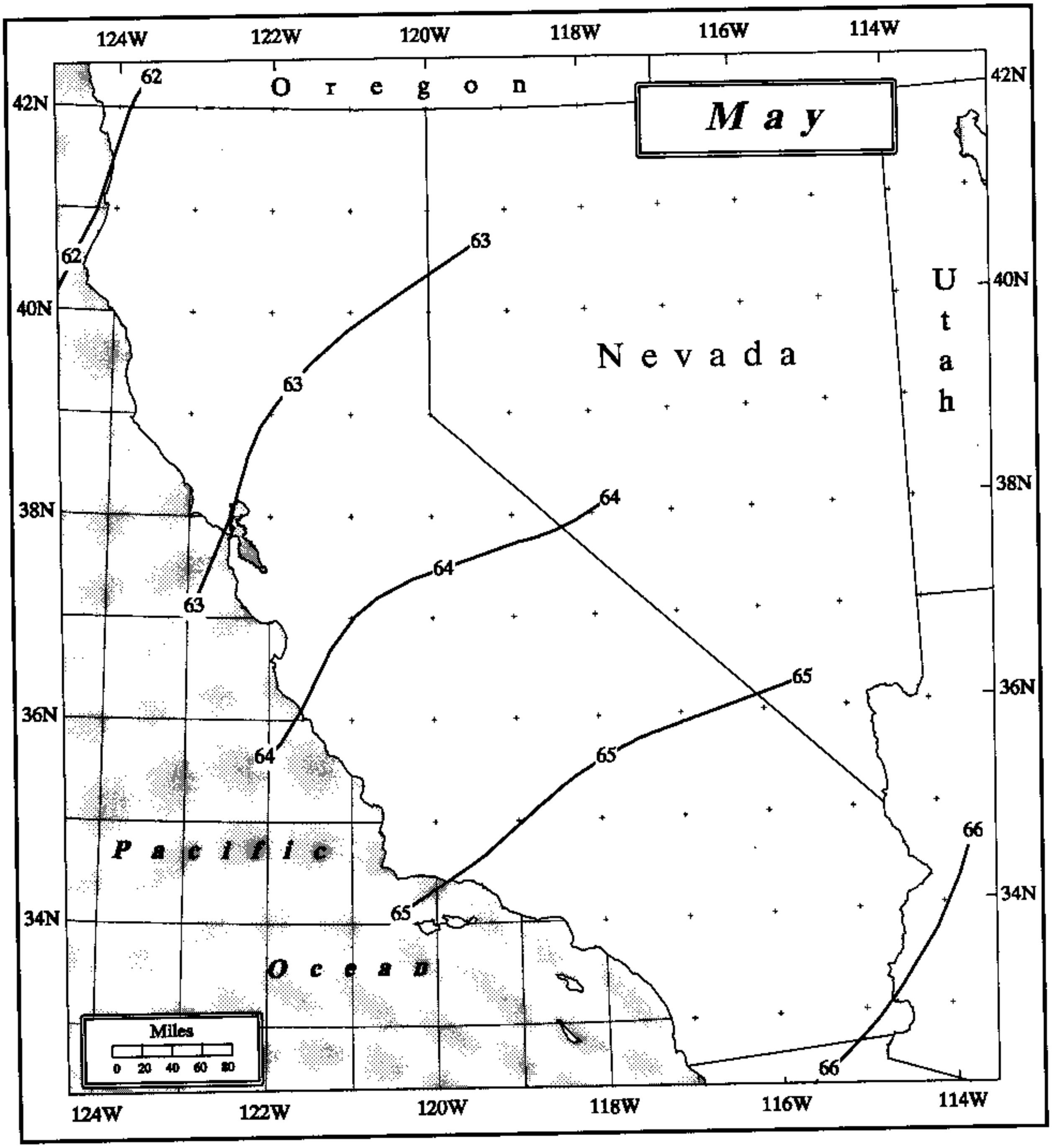

Figure 4.5. *Twelve-hour maximum persisting 1000-mb dewpoints for May (°F).*

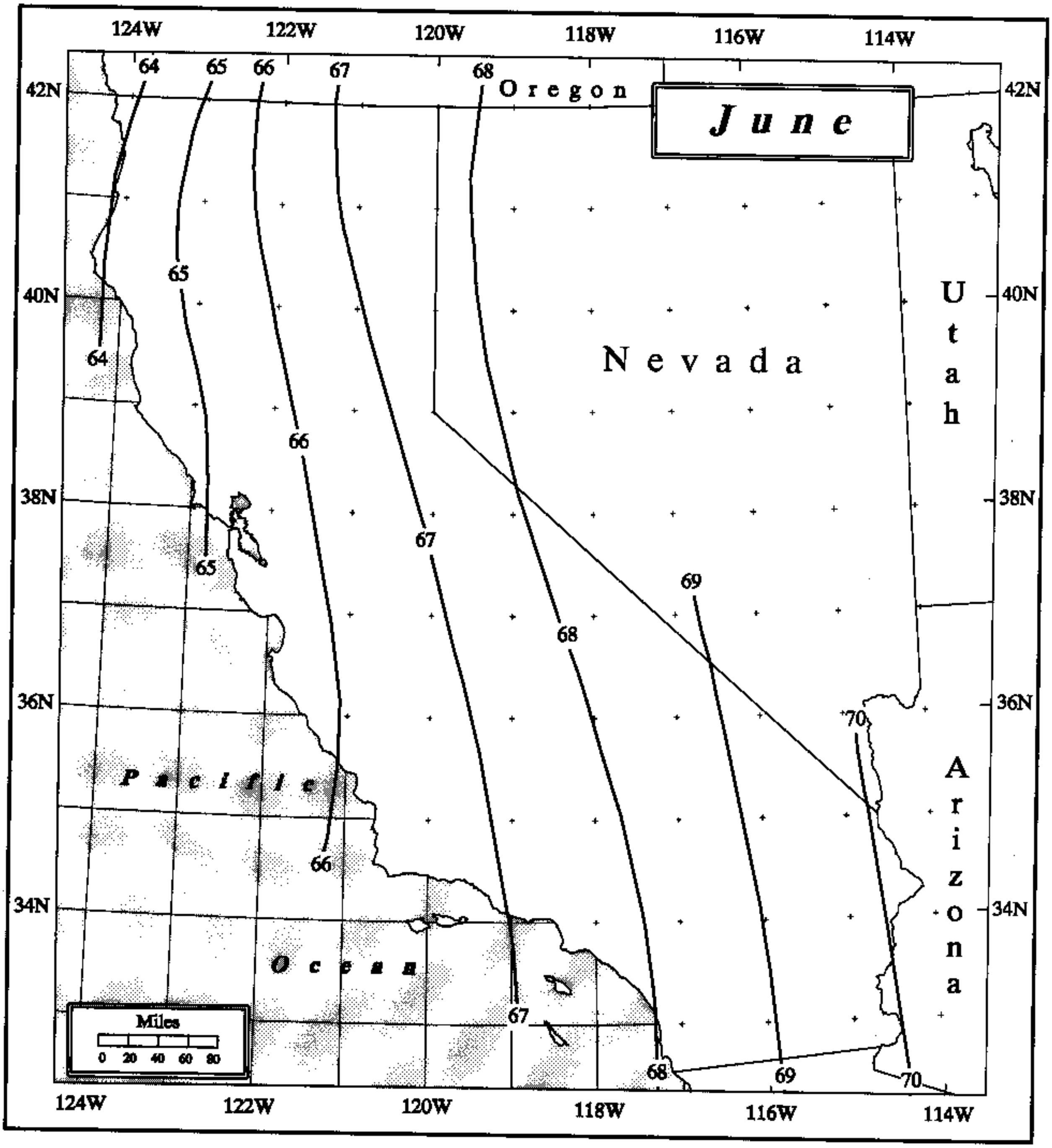

Figure 4.6. *Twelve-hour maximum persisting 1000-mb dewpoints for June (°F).*

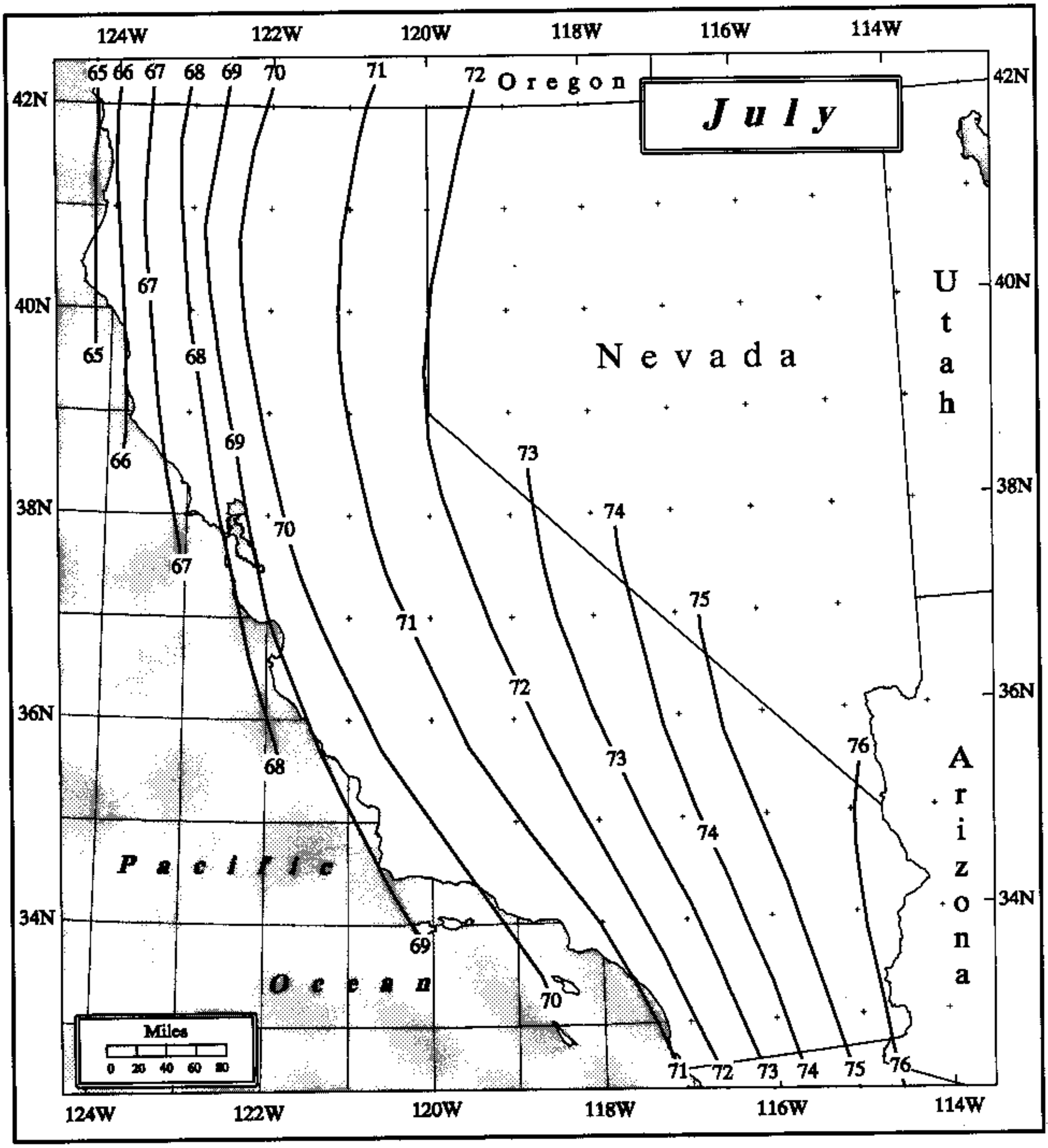

Figure 4.7. *Twelve-hour maximum persisting 1000-mb dewpoints for July (°F).*

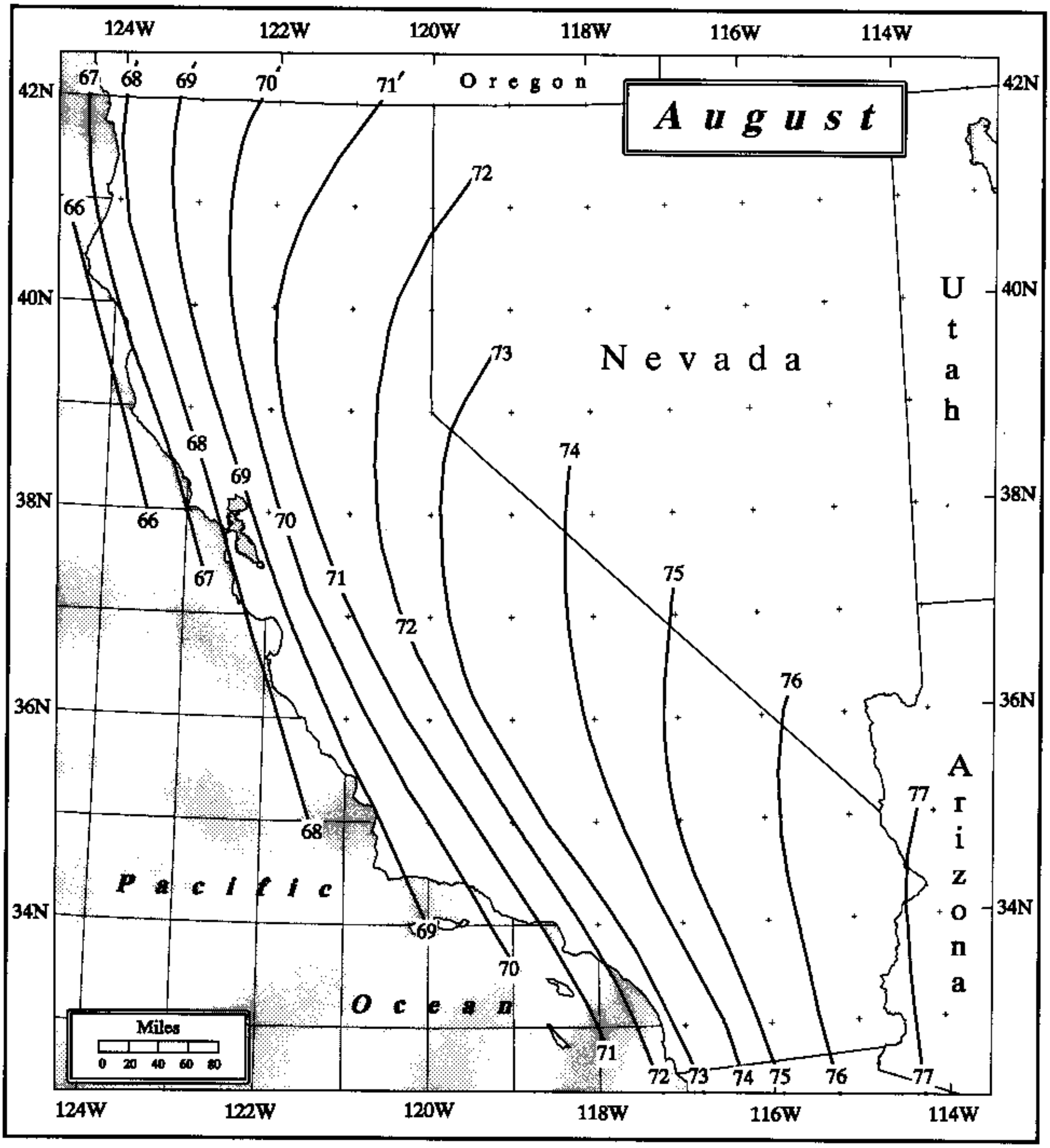

Figure 4.8. *Twelve-hour maximum persisting 1000-mb dewpoints for August (°F).*

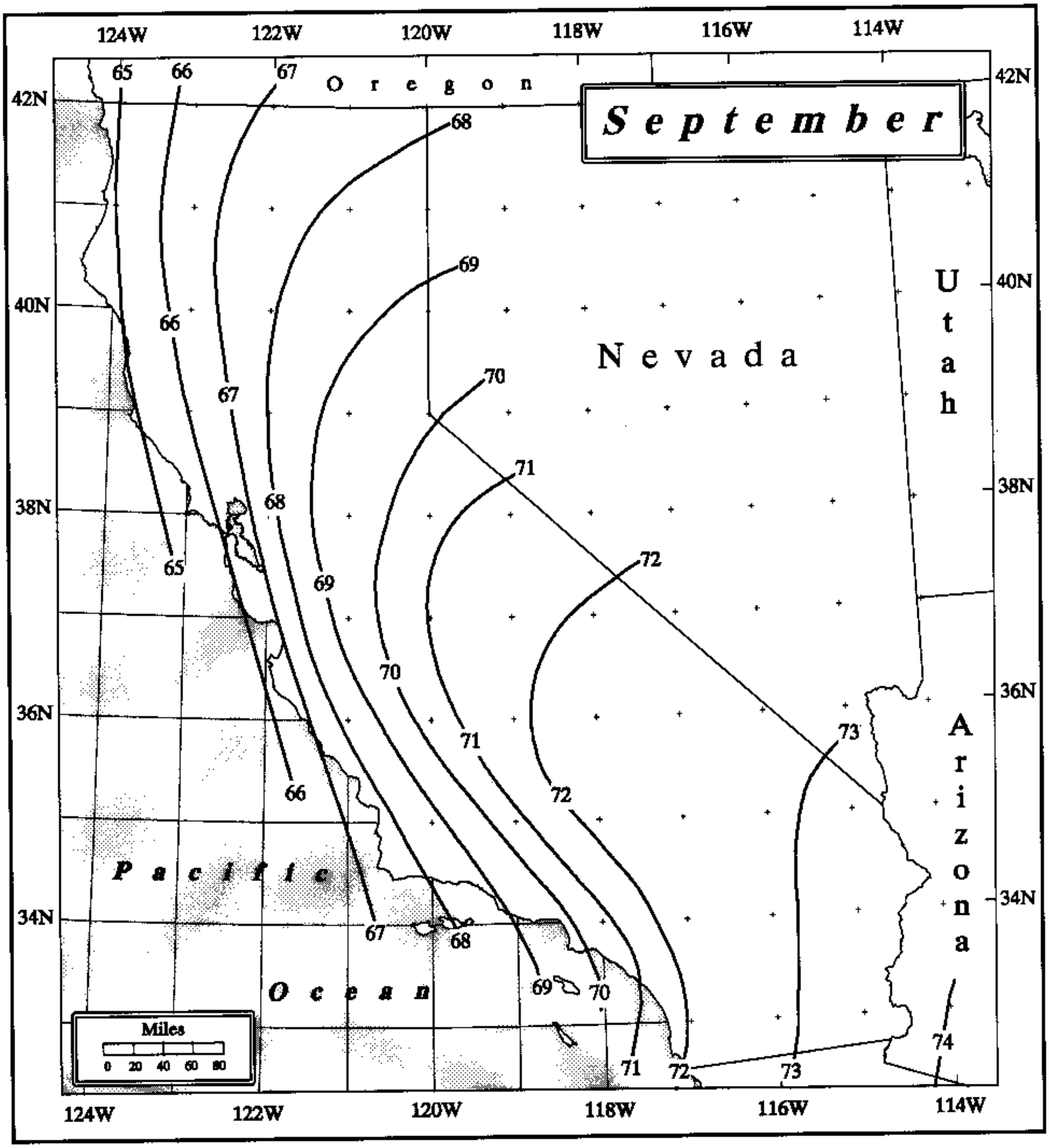

Figure 4.9. *Twelve-hour maximum persisting 1000-mb dewpoints for September (°F).*